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Decay and interference effects in visuospatial short-term memory

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Abstract. The method of constant stimuli was used to examine the accuracy with which two-dimensional spatial information can be represented in mental images. In experiment 1, subjects had to decide which of two successively presented two-dot separations was wider. Over the range of interstimulus intervals employed (0 to 30 s), there was a linear relationship between interstimulus interval and spatial interval thresholds.

In experiment 2 subjects' abilities to represent accurately more than one spatial interval at a time was investigated. Three dot pairs were presented, but only two pairs were to be compared, the third being completely irrelevant to the task. This manipulation doubled thresholds (relative to a two-dot-pair control condition), whether or not subjects were obliged to attend to the irrelevant dots. Overall, the results suggest that mental representations of spatial information may be temporally durable, but only in the absence of extraneous stimuli. The latter not only disrupt memory for spatial information, but appear to have obligatory access to it.

1 Introduction

Visual imagery has attracted a great deal of experimental investigation over the past twenty years, inspired principally by the research programmes of Shepard (eg Podgorny and Shepard 1978; Shepard and Cooper 1982) and Kosslyn (eg Finke and Kosslyn 1980; Kosslyn 1980). These researchers have drawn attention to the apparent similarities in many cases between the end results of imaginal and perceptual processes (reviews in Finke 1985; Farah 1988).

One issue which has received less attention is the extent to which visual images can retain spatial information accurately and usefully. One might have expected studies of the 'visuospatial sketchpad', Baddeley's (1986) hypothetical visual short-term memory, to have provided data on these issues; however, investigations into the visuospatial sketchpad seem to have been focused primarily on its capacity to store visually presented verbal material (eg Frick 1988; Andrade and Meudell 1993).

There are some notable exceptions to this generalisation, however. In studies such as those on capacity limitations in mental imagery (eg Attneave and Curlee 1983; Kerr 1987) it is suggested that there are limitations on the amount of spatial information which can be represented accurately in a mental image. These authors used a task which involved subjects having to imagine two-dimensional or three-dimensional 'grids', around which they had mentally to traverse a path in response to the experimenter's directions. Once the grids exceeded a certain size, subjects became unable to maintain the grid images with sufficient reliability to perform the task.

These experiments are compatible with Kosslyn's (eg 1975, 1980) computational model of imagery, which suggests that visual images are not passive entities, but states which have to be actively maintained by the imager. However, the imaginal spatial manipulations demanded of the subject in these experiments are of a relatively coarse kind.

None of these experiments provides information on how long an image of a given level of complexity can be maintained, and what factors affect its maintenance. I am aware of relatively few studies on such factors, and these have produced somewhat inconsistent results. Some research suggests that there is relatively rapid deterioration of memory for visual-spatial information. Dale (1973) found that the accuracy of memory for the position of a dot in a 12 inch square declined markedly with increases in the duration of the retention interval. After a rapid decrease in accuracy over the first 2 to 4 s, performance reached an asymptote. Harvey (1986) examined short-term memory for complex gratings comprised of seven widely-differing spatial frequencies, and reported relatively rapid deterioration of memory over a 10 s interstimulus interval (ISI). On a somewhat smaller spatial scale, Fahle and Harris (1992) investigated short-term memory for vernier offsets, and found that performance deteriorated with time, thresholds after 8 s being approximately double those obtained with a 1 s ISI.

In contrast, other researchers have found near-perfect retention of visual-spatial information over prolonged time periods. Regan (1985) examined memory for the spatial frequency of a simple grating. Retention was measured with a two-alternative forced-choice procedure: subjects saw two gratings, separated by a variable ISI, and had to decide whether the second grating had a higher or lower spatial frequency than the first. Using this method, Regan (1985) found that subjects' thresholds were almost as accurate with a 20 s ISI as they were with a 0.4 s ISI. In a series of experiments, Magnussen and his colleagues have similarly demonstrated that memory for gratings containing a single spatial frequency is virtually perfect over retention intervals of up to 30 s, for spatial frequencies from 5 to 20 cycles $\deg^{-1}$ (Magnussen et al 1988, 1990, 1991).

Some of the apparent discrepancies in published reports on memory for visually presented spatial information may simply have arisen because of differences between the tasks and procedures used. Since there is some evidence that large and small spatial separations may be processed by different mechanisms (eg Levi and Westheimer 1987; Morgan and Regan 1987; Wang and Levi 1994), the apparent contradiction between the data of Fahle and Harris (1992) and Magnussen et al (1991) might reflect real differences in the durability of the different types of representation involved. The mechanisms underlying memory for small-scale spatial relationships might be more susceptible to disruption than those responsible for large-scale relationships. Alternatively, if large-scale-separation judgments require the joint operation of more than one mechanism, then addition of each extra mechanism may add a further source of potential noise to judgments.

It is harder to explain the discrepancy between the data of Harvey (1986), obtained with the use of complex gratings, and those of Regan (1985) and Magnussen et al (1991), who used stimuli with a much simpler spatial-frequency content. Magnussen et al (1991) suggest that the discrepancies could be explained if visual short-term memory is organised as a series of stores along the spatial-frequency spectrum. Memory for complex gratings might decay as a consequence of interference between these stores at the retention or retrieval stages. An alternative possibility is that memory for harmonically simple, periodic stimuli (eg single spatial frequencies) might be based on some lower-level mechanism than that for more complex stimuli, and that this low-level mechanism is more resistant to the effects of the passage of time.

Since there are so few studies which have been focused directly on the question of how durable accurate spatial representations are, and what factors affect this durability, it was decided to investigate these issues further. Performance on a spatial-interval discrimination task was used as a probe, and, as with Regan's (1985) and Magnussen et al's (1990, 1991) studies, a two-alternative forced-choice procedure was used. However, in contrast to these researchers, I used stimuli consisting of pairs of widely separated dots, ie stimuli which were spectrally broadband and aperiodic.

The two experiments reported here address the following questions. In experiment 1 I looked at how long subjects were able to maintain an accurate mental representation of a single spatial interval. Do representations deteriorate in accuracy gradually or abruptly? As mentioned earlier, extant studies provide conflicting data on this point. One possibility is that visual memory for spatial frequency is somehow different from visual memory for more complex, aperiodic stimuli. Burbeck and Yap (1990a, 1990b) and Wang and Levi (1994) are amongst the authors who have suggested that an analysis of the spatial-frequency content of a scene is by itself insufficient for positional acuity judgments, and that, especially at larger separations, some other mechanism (for example, information based on 'local sign') must also be involved. Perhaps when other mechanisms come into play, this has consequences for visual memory (for example, by adding an additional source of noise). Consequently, in the present experiments I examined the time-course for memory decay of widely spaced spatial intervals, defined by dots. These stimuli were separated by over 6 deg, a separation which is probably too large to be handled by a single spatial-frequency channel (Wilson and Gelb 1984).

Experiment 2 focused on two questions. First, to what extent can subjects maintain and use multiple representations? This is an issue left unaddressed by the literature on positional acuity, where subjects are almost always asked to make a single decision about a single stimulus attribute on any given trial. Can a subject encode and retain information about more than one spatial relationship at a time, and selectively use this information? The second question addressed is the extent to which the initial representation is resistant to disruption. If two successively presented stimuli are being compared, what happens if other, similar, stimuli are presented in the time interval between them? Subjects show an impressive ability to perform accurately on spatial interval tasks despite the simultaneous presence of considerable 'noise' (eg Burbeck and Yap 1990a; Morgan et al 1990b). One might therefore expect subjects to be equally able to disregard noise which is temporally as well as spatially discriminable from the stimuli to be compared. Again, only limited data exist on this point. Magnussen et al (1991) investigated the effects of interposing an irrelevant 'noise' grating between two gratings that subjects were attempting to compare. The greater the difference in spatial frequency between the noise and reference gratings, the worse thresholds became. This effect reached an asymptote when the noise grating was an octave either higher or lower than the reference grating.

Experiment 2 of the present study involves a more-detailed look at the effect of irrelevant stimuli on spatial memory, following on from Magnussen et al's work. Using dot stimuli similar to those in experiment 1, I directly compared subjects' ability to maintain an accurate spatial memory under a number of conditions in which irrelevant stimuli were presented. Two conditions are of particular interest, because they allow a comparison of performance under conditions of attended and unattended noise. In one condition, subjects attempted to retain two accurate spatial representations at once, whereas in another condition subjects attempted to maintain just one accurate representation in the face of an extraneous stimulus which they knew they should ignore because it was irrelevant to the task.

2 Method

2.1 *General procedure*

A two-alternative forced-choice procedure was used to determine thresholds for spatial interval estimation.

Stimuli were presented under computer control on an IBM PS/2 computer with VGA colour monitor. The screen subtended approximately 24.5 deg horizontally by 18.6 deg vertically at the viewing distance used (60 cm from the screen). Observations were made in a windowless room under the normal fluorescent lighting of that room.

A stimulus consisted of a pair of white dots (with an approximate luminance of 300 cd m^{-2}) on a black background (approximate luminance 105 cd m^{-2}). Each dot was 3 mm square, thus subtending a visual angle of approximately 17 min arc × 17 min arc. Subjects were presented with two or three stimuli in succession, according to the experiment (see below). The last stimulus presented was always a standard. This was preceded by one or more sets of comparison stimuli. All stimuli were displayed on the screen for 3 s; unless otherwise stated below, the ISI was 1 s.

The stimuli were presented in the approximate centre of the screen. The precise position of each stimulus was varied horizontally and vertically, in order to forestall the use of any strategies by the subjects. With respect to the preceding stimulus, a pair of dots was shifted to the left or right by 0, 9, or 18 mm horizontally and, independently of this, was displaced vertically by 0, 12, or 24 mm upwards or downwards.

The horizontal separation between the standard pair of dots used in both of the experiments described below was nominally 65 mm (approximately 6.2 deg), measured between dot centres; the actual length varied randomly by 20% from presentation to presentation, in order to prevent the subject from developing an internal, implicit 'standard' against which to compare the comparison stimuli. Each comparison stimulus was the same length as the standard, plus or minus a certain amount (the 'cue') whose value varied from trial to trial.

The subject's task was to decide whether the dots in the comparison stimulus were closer together or farther apart than those in the standard (ie to detect whether the addition of the cue made the comparison stimulus wider or narrower than the standard), and to press one of two keys in response. Each threshold determination was based on 100 decisions of this kind. Subjects were asked to perform the task as accurately as possible: the program could be 'paused' after any of the 100 trials, and subjects were encouraged to make use of this facility to allow themselves a short break if they felt fatigued at any point within a session. Subjects were unaware of the aims in these investigations, and they received no feedback about their performance during the experiment.

Stimuli were presented under computer control, by means of an adaptive method of constant stimuli. This was similar to Taylor and Creelman's (1967) 'parameter estimation by sequential testing' (PEST), except for the way in which the subject's threshold was finally determined. Whereas Taylor and Creelman took as their threshold estimate the subject's performance on the final trial of a series, in the present experiments the data from all 100 trials were used in the threshold estimation: the data were subjected to logit analysis, and the measure of threshold taken was the slope of the fitted function.

All data are presented as Weber fractions (ie difference thresholds expressed as percentages of the nominal separations between the dots shown as the standard stimulus).

3 Experiment 1: the effect of interstimulus interval on spatial interval judgments

3.1 *Method*

Five subjects took part, all with normal or corrected-to-normal vision. One (the author) was highly experienced on psychophysical tasks; the other four subjects (two males and two females) had never before participated in an experiment like this.

Subjects were presented with 100 trials. On each trial, there were two stimuli to be compared. Each stimulus consisted of a pair of small square white dots on a black background. The stimuli were presented sequentially. First, the subject saw a blank screen containing a message saying that the next trial was about to begin. The screen then cleared, and the first pair of dots was displayed for 3 s. The screen went blank for a certain period of time (the ISI) and then the second pair of dots was presented for 3 s. The screen became blank again, until a response was made. The subject's task was to decide whether the horizontal distance between the first pair of dots was smaller or larger than the corresponding distance between the second pair of dots.

The independent variable was the length of the ISI, ie the duration of the time interval between the offset of the first stimulus and the onset of the second stimulus. There were seven different conditions, each of which involved one of the following durations of ISI: 0, 1, 5, 10, 20, or 30 s. (The ISI in the zero-ISI condition was actually about 40 ms, the refresh rate of the screen).

Increases in ISI inevitably lead to increases in individual trial length, and hence increases in overall run duration. This might have led to a concomitant increase in subjects' levels of fatigue, boredom, etc. The seventh condition was an attempt to control for these effects in the following way. Each trial lasted 30 s, but the ISI was only 1 s. The first stimulus was presented at a randomly determined time after the beginning of the trial; the second stimulus was presented 1 s after the first stimulus; and then the subjects had to withhold their response until the remainder of the 30 s period had elapsed. (Both of the stimuli were presented for 3 s, as in the other conditions). This provided subjects with the shortest ISI, while maintaining overall run duration at its maximum.

3.2 *Results*

Figure 1 shows the mean two-dot separation thresholds for the six subjects, as a function of ISI. (Note that the condition in which each trial lasted 30 s, but the ISI was only 1 s, has been omitted from this graph.) With ISIs of 0 or 1 s, subjects showed Weber fractions of under 5%. However, as ISI increased, thresholds became progressively worse, doubling by the time ISI reached 30 s. Even with only five subjects, a one-way repeated-measures ANOVA revealed a significant difference between the six ISIs ($F_{5,20} = 4.33$, $p < 0.01$). A trend analysis showed that the linear trend suggested by figure 1 was statistically significant ($F_{1,20} = 21.12$, $p < 0.001$). No higher trend approached significance. (For a quadratic trend, $F_{1,20} = 0.042$, ns.) However, note that even at 30 s ISI the mean threshold was still under 10%.

For the condition in which each trial lasted 30 s but the ISI was only 1 s, the mean threshold was 4.2% (SD 1.3%). This is similar to that for the 1 s ISI condition, suggesting that the deleterious effects on performance of the 30 s ISI are not attributable merely to boredom or fatigue per se.

These results suggest that subjects can construct an accurate representation of the spatial relationship displayed in the stimulus first presented, and compare this with the second stimulus while the latter is physically present. With the passage of time, the accuracy of the spatial information contained in the representation of the first stimulus progressively deteriorates (as reflected in the steadily worsening thresholds); however, it is still tolerably accurate even after 30 s have elapsed.

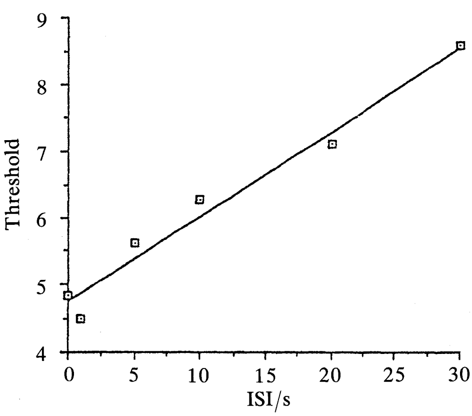

Figure 1. Two-dot separation thresholds (percentage dot separation) as a function of interstimulus interval, ISI, for the six subjects.

4 Experiment 2: the effects of spatial noise on spatial-interval judgments

It is suggested from the first experiment that subjects can maintain a reasonably accurate representation of spatial information for a considerable time. In this experiment the extent to which such a representation can be maintained in the face of interference from a second representation of spatial relationships is investigated.

4.1 *Method*

Twelve subjects took part in this experiment. All had normal or corrected-to-normal vision. None of the subjects had prior experience in performing psychophysical tasks, and all were naive with respect to the hypotheses under investigation.

Subjects were presented with three pairs of dots in succession, A, B, and C. Pair C were a standard: the distance between these two dots was compared with that between the dots in pairs A or B, as follows. There were four conditions (order of presentation was counterbalanced across subjects):

(a) *Condition 1 (control condition: A vs C).* Only pairs A and C were presented. Subjects had to decide whether the horizontal distance between the pair of dots in pair A was larger or smaller than the distance between the dots in pair C. This condition is identical to the 5 s ISI condition in experiment 1.

(b) *Condition 2 [(A or B) vs C].* Three pairs of dots were presented in turn. After the third pair of dots was presented and had disappeared from view, the subject was instructed to compare pair C with one of the first two pairs of dots presented—ie either with pair A or with pair B. (The instructions consisted of both a displayed verbal message and a short tone—a high tone if the comparison was to be between pairs A and C, or a low tone if the comparison was to be between pairs B and C.) On 50% of trials the subject had to compare A and C and on the remaining 50% had to compare B and C. However, these two tasks were randomly interleaved. Thus the task was to look at three pairs of dots, but to make a comparison between only two pairs, with the subject unaware of which pairs were to be compared until after all three pairs had been presented. Since the subject had no way of knowing in advance which of the first two pairs of dots was to be used in the comparison, accurate performance on this task necessitated an attempt to construct accurate representations of all three pairs of dots, but use only two of them for the experimental task.

(c) *Condition 3 (A vs C, ignoring B).* This was identical to condition 2, except that the subject was instructed always to compare pair A with pair C, ignoring B; ie the subject was fully aware that pair B were irrelevant to accurate performance of the task, and could therefore be ignored on all trials. This condition controlled for any mere distractive effects of the second pair of dots, and allowed examination of the effects of noise dots which were not attended to.

On each trial, the separation between the dots in pairs A and B differed randomly: pair B were either closer together or wider apart than pair A. This random alteration was calculated as follows: on each trial, the separation between the dots in pair B was initially set to the same value as for the dots in pair A. Up to 60% of the separation between the dots in pair A was then added to or subtracted from the distance between the dots in pair B before the latter dots were displayed. Thus, given that the dots in pair A were nominally 65 mm apart, the distance between the dots in pair B on any given trial could be any value from 26 to 104 mm.

(d) *Condition 4 (ignore A; B vs C).* Subjects were presented with three pairs of dots, but were told that they could ignore the first pair as they would always be comparing the separations between the second and third pairs. It seems intuitively unlikely that there would be any effect on thresholds of noise dots which preceded the two pairs of dots to be compared, but this condition was intended as a control for trial length and for the complexity of the instructions being followed by subjects.

The difference between dot-pairs A and B was produced in a similar way to in condition 3: on each trial, the separation between the dots in pair A was up to 60% wider or narrower than the separation between the dots in pair B.

4.2 *Results*

The mean thresholds for the control condition (A vs C) and condition 4 (ignore A, B vs C) were identical, at 6.5% of the dot separation (SDs 2.2% and 3.2% respectively). These are slightly higher thresholds than those obtained in the comparable condition of experiment 1 (ie A vs C with an ISI of 5 s).

There was noticeable elevation of thresholds in condition 2 (A or B) vs C, in which subjects had to compare either pair A or pair B with pair C. The mean threshold for this condition was 13.3% (SD 8.8%). Surprisingly, just as much threshold elevation occurred in condition 3 (A vs C, ignoring B), in which subjects had to compare pairs A and C, merely ignoring the intervening dot pair B (mean 13.4%, SD 10.4%).

A one-way repeated-measures ANOVA revealed a significant overall effect of condition ($F_{3,33} = 6.46$, $p < 0.001$). Newman–Keuls tests showed that there was no significant difference between the control condition and condition 4, nor between conditions 2 and 3. There were significant differences ($p < 0.05$) between each of the former two conditions, and each of the latter two conditions.

These results suggest that accuracy in maintaining a representation of a spatial interval can be reduced either (a) by attempts to encode and retain information about a similar interval, or (b) by the mere interposition of an irrelevant but similar stimulus between the stimuli to be compared. Presentation of a second stimulus interfered with performance on the experimental task, whether or not the stimulus was attended to. However, this second stimulus had to be interposed between the stimuli being compared, for it to exert any effect. The absence of any effect of the extraneous stimulus in condition 4 (ignore A; B vs C) suggests that the extraneous dot pairs in conditions 2 and 3 did not impair performance merely by distracting the subject, by lengthening the interval between the stimuli to be compared, or by increasing the nonperceptual cognitive demands made by the task.

5 Discussion

The results of experiment 1 show that subjects were able to construct and maintain an accurate representation of spatial intervals over comparatively long ISIs, if no other stimuli were presented to interfere with this representation. With ISIs of up to 5 s, subjects were able to detect reliably a difference between the two stimuli presented which was equivalent to about 5% or less of the interval being judged. This result is typical of performance on spatial-interval tasks (Morgan 1991).

Spatial interval estimation deteriorated slowly, in a linear fashion over time. However, even with an ISI of 30 s, the effects of mere passage of time were relatively small. Although thresholds were double those obtained with shorter ISIs, performance on the task was still reasonably accurate, with thresholds at less than 10% of the interval being judged. The limits of subjects' abilities to retain information about a spatial extent were clearly not reached here. However, since the use of 30 s ISIs meant that each individual threshold determination took over 30 min, some technique other than the method of constant stimuli would have to be used to investigate this issue further. These results, involving widely separated aperiodic and spatially broadband stimuli, support and extend previous reports by Regan (1985) and Magnussen et al (1990, 1991) for simple spatial frequency stimuli, that visual-spatial memory can under certain circumstances remain accurate over prolonged periods of time.

The high level of accuracy of performance over extended ISIs in experiment 1 contrasts with the results of Harvey's (1986) and Dale's (1973) experiments; Harvey found that discrimination between two complex gratings deteriorated exponentially, so that subjects' performance after 10 s was almost twice as poor as it had been at 10 ms. Dale (1973) found that accuracy of memory for the position of a dot in a 12 inch square declined rapidly over the first 2 to 4 s of the retention interval, and then reached an asymptote. In contrast, the results of experiment 1 are much more like those reported by Regan (1985) and Magnussen et al (1990, 1991).

Procedural differences between these studies preclude overdetailed comparisons. However, one possible reason for the apparent discrepancy between these two sets of studies may be the type of task involved. In the last three studies *relative* separation of stimuli was examined, whereas Harvey and Dale were concerned with *absolute* spatial location of stimuli. In Dale's experiments, subjects could in principle perform the task in one of two ways: by remembering the position of the dot relative to one or more sides of the square within which it was contained, or by remembering its position in absolute terms. Since the positions of all stimuli were chosen to be as difficult as possible (well away from the edges of the square), it is likely that subjects adopted the latter strategy, and attempted to remember the absolute position of the dot.

Harvey's experiment at first sight appears to be concerned with memory for spatial frequency, but a close examination of his procedural details suggests that this too might be more of a test of memory for absolute position. Subjects were required to identify the 200 trials out of 1100 in which one of ten complex gratings was presented twice in succession. Since all of the gratings contained identical spatial frequencies, the task could not be achieved by subjects responding to spatial frequency alone, but presumably was done on the basis of spatial phase—the position of the spatial frequency peaks and troughs relative to each other. The task would thus consist of remembering the absolute position of the bright and dark bars in the first stimulus presented, for long enough to compare them with the second stimulus. This is a rather different spatial task from that studied in the present experiments and by Regan and Magnussen et al; in these three studies, phase was varied randomly between stimulus presentations and hence was unavailable to subjects as a cue. (Note that with Harvey's paradigm, the phase differences between a stimulus pair might have acted as an additional cue for subjects at very brief ISIs: deciding that two gratings were different could have been achieved solely on the basis of the apparent-motion cue that would have been produced by the change in phase. Thus impairment of performance with increased ISI might have been partially due to the progressive loss of this apparent motion cue, rather than to decay in the memory trace per se.)

Whether or not one considers that these diverse studies are tapping the operation of the same visual-spatial memory system, one still has to explain the progressive (albeit small) deterioration in performance with increasing ISIs in the present experiment. In fairly general terms, this could be explained in terms of Kosslyn's (1980) computational model of imagery, if the periodic 'updating' or 'refreshing' of the visual image led to a slight degradation in its quality each time it occurred. This is broadly equivalent to the 'memory-diffusion' hypothesis of Kinchla and Smyzer (1967), and to Fahle and Harris's (1992) interpretation of their data on memory decay for vernier stimuli in terms of the progressive addition of noise to memory of the separation between the two lines which comprise the stimulus.

Since the precise mechanisms underlying spatial-interval discrimination are not yet clear, it would be premature to speculate further on exactly how temporal delay might add 'noise' to the underlying memory representation. However, the similarity between the present results and those of Regan and Magnussen et al raises an interesting possibility that whether one is attempting to retain a memory of a single spatial frequency or a somewhat more complex stimulus, the representation in memory of the stimulus-separation information might be identical. Regan (1985), Magnussen et al (1991), Burbeck (1987), and Wang and Levi (1994), have all argued that spatial-interval judgments involve representations at a higher level of abstraction than the early low-level stages of vision. Burbeck (1987), for example, has distinguished between 'primary' and 'secondary' representational stages in spatial processing. All that might be retained in the secondary representation stage is some representation of the separation between two stimuli, regardless of how those stimuli might have been defined initially in the primary representation (ie whether the separation was between two dots or between successive peaks in a sinusoidal grating).

It is suggested for the results of experiment 2 that the processes involved in retaining accurate information about spatial relationships are susceptible to disruption from similar stimuli, and that these processes can deal effectively with only one spatial interval at a time—whether or not extraneous spatial intervals are attended to. In condition 2 [(A or B) vs C] subjects were confronted with three pairs of dots and asked to compare the distance between the dots in either the first or the second pair with the distance between the dots in the third pair. This is clearly a rather complex task, and it is hardly surprising that subjects' thresholds for spatial-interval discrimination were elevated in this condition. To perform the task, a subject presumably had to construct and retain three representations: one for the distance between the first two dots presented; another for the separation between the second pair of dots, and a third for the distance between the third pair of dots. These three representations would have to be maintained until the subject was cued about which of the first two representations was to be compared with the third. Thus thresholds were heightened either because subjects were distracted by the complexity of the task, or because the systems involved in visual-spatial memory are incapable of retaining more than one spatial interval at a time, at least with any high level of fidelity.

In condition 3 (A vs C, ignoring B), the stimuli (and their temporal relationship) were identical to those in condition 2, but the task was much simpler: subjects had only to construct and maintain some representation of the distance between the first pair of dots and compare that representation with the distance between the third pair of dots. In this latter task, subjects were instructed merely to look at the monitor screen while the second pair of dots was presented, and they knew that they did not have to attempt, at least consciously, to encode the distance between the middle pair of dots. An additional advantage in this condition is that subjects did not have to maintain a representation of the third pair of dots for any length of time: they could compare their internal representation of the first pair of dots with the perceptual representation of the third pair while the latter was physically present before them. This was not the case in condition 2; here subjects had to defer their judgment until the third pair of dots had disappeared from view, because it was only then that the message and tone were presented telling subjects which of the first two dot pairs should be compared with the third. Despite the advantages of condition 3 over condition 2, in the former condition the middle pair of dots exerted a clear effect on subjects' performance, as marked as when subjects were attempting to retain information about the distance between both of the initial two pairs of dots in condition 2.

Experiment 2 thus shows first that subjects can retain information about more than one spatial interval at a time, but only at the expense of some accuracy, and second, that stimuli which the subject consciously knows are irrelevant to the task at hand may nevertheless affect performance.

It is true that the two-dot-pairs control condition of experiment 2 was much simpler to perform than any of the three-dot-pairs conditions. This was especially so in the case of condition 2 [(A or B) vs C], in which subjects had not only to try to remember two different spatial intervals and compare them with the third one presented, but also had to remember and follow the instructions on which of the first two dot pairs was to be used for the comparison. The results of condition 4 of the second experiment (ignore A; B vs C), argue against this added complexity being the cause of the obtained results. In condition 4, subjects were presented with three pairs of dots and asked to ignore the first pair. The task was thus essentially the same as in condition 3 (A vs C, ignoring B), except that in the former condition the irrelevant dots preceded the dot pairs to be compared, while in the latter condition the irrelevant dots were interposed between the dot pairs being compared. Only in the latter condition, however, was any elevation in thresholds obtained.

The results of experiment 1 make it unlikely that the results of experiment 2 were due merely to the difference in ISI between condition one (A vs C) and conditions 2 [(A or B) vs C] and 3 (A vs C, ignoring B) in the second experiment. The ISI in condition 1 was 1 s; the ISI in condition 2 was either 5 s or 1 s (depending on whether A or B had to be compared with C); and the ISI in condition 3 was always 5 s. However, the results of experiment 1 showed that ISI per se has little effect on performance, at least within this range of values.

Last, it should be pointed out that the results of experiment 2 have proved to be highly replicable: a separate experiment involving twenty subjects performing the first three conditions of experiment 2 (not reported in detail here for reasons of space) closely reproduced these findings.

The results of experiment 2 are consistent with Toms et al's (1994) conclusion that "irrelevant visual material has obligatory access to a specialised visual store, interfering with storage of visuospatial material in working memory" (page 141). However, the precise mechanism by which the irrelevant dots exert their disruptive effects remains unclear. Magnussen et al (1991) found threshold elevation for spatial-frequency discrimination when an irrelevant grating was interposed between each pair of gratings being compared. Moreover, thresholds varied systematically as a function of the relative spatial frequency of the irrelevant and test gratings involved. As Magnussen et al point out, it is difficult to dismiss the latter finding (and by implication the results of the present study) as due merely to nonspecific distraction. Given the similarity between their results and those obtained in studies of spatial-frequency masking and adaptation, Magnussen et al are at pains to rule out interpretations of their findings in these terms. They claim that the long ISIs between successive stimuli gave little time for low-level sensory processes such as those involved in masking to operate. Such low-level explanations are even less likely to be plausible as an account of the results of the present experiments since, on any given trial, not only were successive dot pairs clearly demarcated in time (as in Magnussen et al's experiments) but they were also clearly separated spatially (since they appeared at different locations on the monitor screen). One possible means by which visual noise might exert its effects in the current experiments and Magnussen et al's studies is if the noise is either averaged with the existing representation or overwrites it altogether. The data available at present do not enable one to discriminate between these two explanations (and there may of course be other interpretations).

Taken together, the results of Regan (1985), Magnussen et al (1991), and the present experiments allow one to suggest the following conception of short-term visual-spatial memory. First, it is able to retain visually presented spatial information with a high level of fidelity for prolonged periods of time, although some loss of precision occurs eventually. Second, it has a highly limited capacity to retain information (one spatial interval at a time, as shown by experiment 2). Third, and related to the previous point, the stored information is highly susceptible to disruption from subsequent visual stimulation, whether or not this stimulation is consciously attended to [as shown, using a rather different paradigm, by Toms et al (1994)].

In short, the data are consistent with a conception of visual-spatial storage as a dynamic system which stores information by periodically updating a memory trace. The precise nature of the processes by which the trace is updated remain to be elucidated, and might differ from task to task.

The interference produced by irrelevant stimuli in experiment 2 are somewhat different from those obtained when irrelevant stimuli are presented at the same time as the target stimuli in vernier-acuity and spatial-interval tasks (eg Morgan and Ward 1985; Burbeck and Yap 1990a; Morgan et al 1990b). There is also considerable literature attesting to the fact that subjects can make accurate spatial-interval judgments despite major modifications or perturbations to the stimuli concerned. For example, DeValois et al (1990) found that experienced subjects were able to make highly accurate judgments of relative position despite considerable transformations (eg in size, orientation, or two-dimensional spatial profile) of the stimuli being compared. Spatial-interval acuity—and vernier acuity—can also withstand stimulus motion across the retina at up to 3 deg s^{-1} (Westheimer and McKee 1977; Morgan et al 1983; Morgan and Benton 1986).

In Badcock and Wong's (1990) study, subjects had to decide which of two intervals (demarcated by vertical lines) was the larger. Surprisingly accurate performance was obtained even in the face of considerable amounts of 'spatiotemporal jitter' of the lines during presentation. Badcock and Wong concluded that "the visual system is very resistant to noise produced by spatial jitter when performing a separation discrimination task (page 1558). From the results of the present experiments it is suggested that although the visual system might be capable of dealing with spatial 'noise' very effectively by means of selective attention during the initial *construction* of representations, the *maintenance* of spatial representations is more open to disruption. In this respect, the results of the present study are compatible with Baddeley's (1986) conception of the visuospatial sketchpad as "a system that seems to be specialised for the simultaneous maintenance of spatial or patterned stimuli but ... [which is] ... poorly designed for holding temporal sequences of visual items" (page 143). The results of experiment 2 support Baddeley's suggestion that the visuospatial sketchpad is "... susceptible to disruption by concurrent spatial processing".

However, although disruption does occur, in absolute terms the effects are quite small; no threshold in the experiments described here was over 14% of the spatial interval being judged. Even inexperienced subjects have an impressive capacity for making accurate spatial-interval judgments despite the presence of significant perturbations of the stimuli being viewed.

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